

W-pair Production in Unparticle Physics

Swapan Majhi *

Department of Physics, Baylor University, Waco, TX 76706, U.S.A.

Abstract

We consider the W -pair production for both e^+e^- and hadron colliders in the context of unparticle physics associated with the scale invariant sector proposed by Georgi. We have shown that the unparticle contributions are quite comparable with standard model (SM) specially for low values of non-integral scaling dimension (d_U) and hence it is worthwhile to explore in current and future colliders.

*E-mail: swapan_majhi@baylor.edu

1 Introduction

The novel idea of scale invariance plays a crucial role in both physics and mathematics. For example, phase transition and critical phenomena are scale invariant at critical temperature since all other length scale are considered as fluctuations which are equally important as well. In particle physics, scale invariance also plays an important role. Conformal invariance, in string theory is one of the fundamental property. This symmetry is broken in renormalisable field theories either explicitly by some mass parameter in the theory or implicitly by quantum loop effects [1]. In low energy particle physics, we observed different particles (elementary or composite) with different masses which is the consequence of such broken symmetry. Nonetheless, there could be a different sector of theory in four space-time dimensions which is exactly scale invariant and very weakly interacting with our low energy world (i.e. with standard model (SM) particles).

Recently, Georgi [2] inspired by the Banks-Zaks theory [3], proposed a scale invariant sector (BZ) with non-trivial infrared fixed point. In such scale invariant sector, there are no particles since there is no particle state with a definite nonzero mass. Such sector is made of “unparticles”. This BZ sector interacts with SM sector through exchange a very heavy (unspecified) particles with a large mass scale M_U . Below this scale M_U , two sector interacts like a non-renormalisable theory which suppressed by powers of M_U . On the other hand, scale invariance in the BZ sector emerge at an energy scale Λ_U . The renormalisable couplings of the BZ field induce dimensional transmutation [1] and the scale invariant unparticle emerge below an energy scale Λ_U . Below the scale Λ_U , the BZ sector is matched onto the unparticle operator and the nonrenormalisable interaction is matched onto a new set of interactions between SM and the unparticle fields with small coefficients. Such theory has very interesting phenomenological consequences [2, 7–46].

In this article, we concentrated on W -pair production in both e^+e^- and Hadron collider. We consider only two types of effective operators - scalar unparticle O_U and the spin-2 unparticle $O_U^{\mu\nu}$. Feynman rules for these operators (which will couple to SM particles) are given in [5]. For the sake of completeness, we are writing down the common effective interactions which satisfy the standard model gauge symmetry.

$$\lambda_0 \frac{1}{\Lambda_U^{d_U-1}} \bar{f} f O_U, \quad \lambda_0 \frac{1}{\Lambda_U^{d_U}} G_{\alpha\beta} G^{\alpha\beta} O_U \quad (1)$$

$$-\frac{1}{4} \lambda_2 \frac{1}{\Lambda_U^{d_U}} \bar{\psi} i \left(\gamma_\mu \overleftrightarrow{D}_\nu + \gamma_\nu \overleftrightarrow{D}_\mu \right) \psi O_U^{\mu\nu}, \quad \lambda_2 \frac{1}{\Lambda_U^{d_U}} G_{\mu\alpha} G_\nu^\alpha O_U^{\mu\nu} \quad (2)$$

where the covariant derivative $D_\mu = \partial_\mu + ig \frac{\tau^a}{2} W_\mu^a + ig' \frac{Y}{2} B_\mu$, $G^{\alpha\beta}$ denotes the gauge field (gluon, photon, weak gauge bosons). ψ stands for SM fermion doublet or singlet and λ_i is the dimensionless effective couplings of the scalar ($i = 0$) and tensor ($i = 2$) unparticle operators. The W -pair will be produced through both spin-0 and spin-2 unparticle exchange (as given in eqns.(1,2)) in both e^+e^- as well as hadron colliders.

This paper is organised in the following way. In section 2, we discuss the total cross section and the differential distribution in the case of e^+e^- collider and in section 3, we discuss the total cross section and differential distributions in the case of hadron collider. Finally we conclude in section 4.

2 W -pair production at $e^+ e^-$ collisions

The differential cross section for the process $e^+(p_1)e^-(p_2) \rightarrow W^+(p_3)W^-(p_4)$ is given by

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s} \frac{|p_f|}{|p_i|} \sum_{A,B} \overline{|\mathcal{M}|_{AB}^2} \quad (A, B = U, \gamma, Z, t) \quad (3)$$

where U represents the spin-2 unparticle exchange diagram and t represents the t -channel diagram. p_i and p_f are the three momentum of the initial and final state particle respectively. All the matrix element square are given in the Appendix. By integrating eqn.(3) over angular co-ordinates, one can get the total cross section. For numerical evaluation, we use the following input parameters:

$$\begin{aligned} \alpha &= \frac{1}{137.04} & \sin^2 \theta_W &= 0.23 \\ m_W &= 80.403 & m_Z &= 91.1876 \\ \Gamma_Z &= 2.4952. \end{aligned}$$

We have plotted the W -pair production cross section versus the new scale Λ_U for two LEP-II energies (as shown in Fig.1). From the Fig.1 it is easy to read the upper bound on Λ_U for various values of d_U on the basis of SM measured value of cross section [47] at 95% C.L.(horizontal lines). By combining these two results, we put the upper bound for Λ_U at 95% C.L. which is given in Table 1.

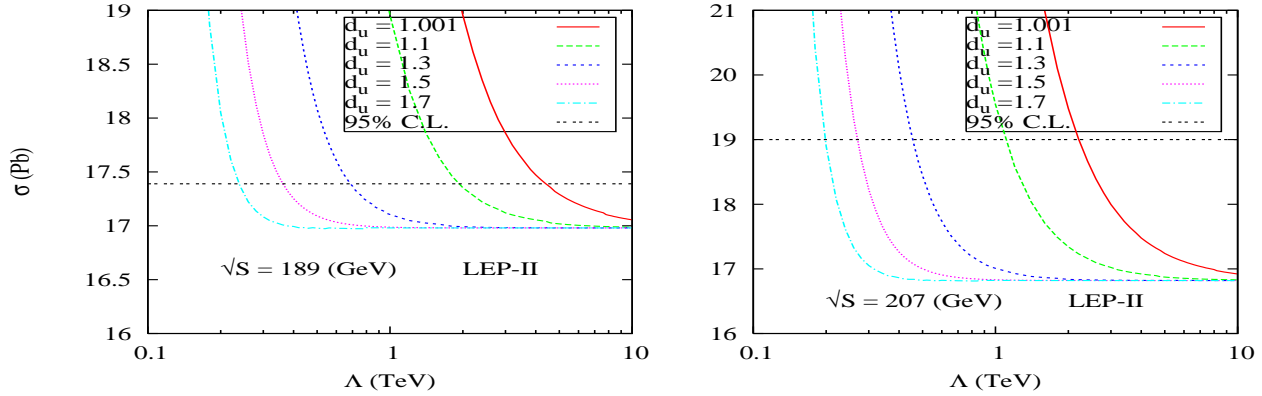


Figure 1: The W -pair production cross section as a function of new scale Λ_U with various values of d_U and $\lambda_i = 1 (i = 0, 2)$.

d_U	Λ_U (TeV)
1.001	4.23
1.1	1.88
1.3	0.68
1.5	0.37
1.7	0.25

Table.1 Limits on Λ_U from the LEP-II data [47] at 95% C.L.

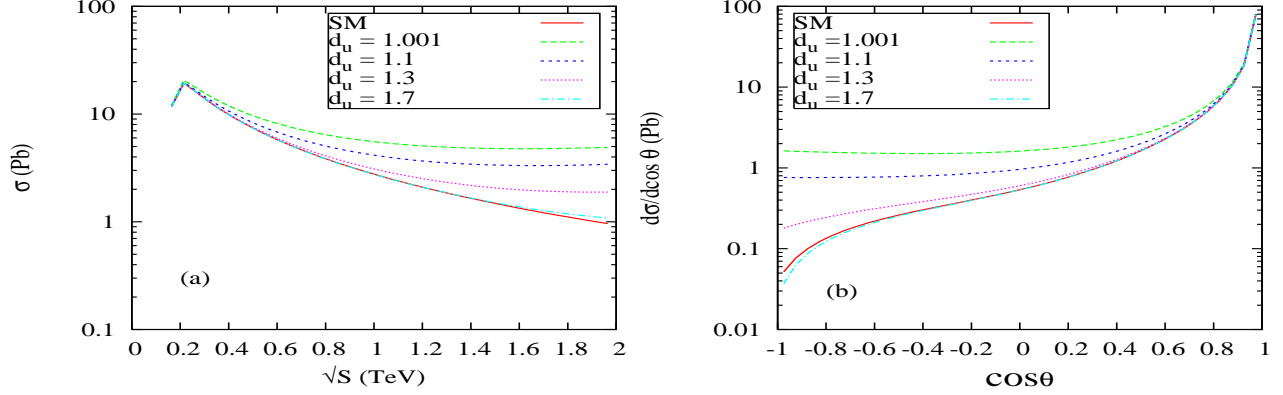


Figure 2: (a) The W -pair production cross section as a function of center of mass energy \sqrt{S} and $\Lambda_U = 1$ TeV, $\lambda_i = 1$ ($i = 0, 2$) (b) Angular distribution at $\sqrt{S} = 0.5$ TeV with $\Lambda_U = 1$ TeV, $\lambda_i = 1$ ($i = 0, 2$) All the curves are due to both contribution SM plus unparticle physics (including interference) except labeled by “SM”. The label “SM” implies only SM cross section.

In Fig.2a, we have plotted the total cross section as a function of center of mass energy for various values of d_u . From the figure, it is clear that for $\sqrt{S} > 500$ GeV, the spin-2 unparticle exchange contribution is significant compared to SM. As $d_u \rightarrow 1$, the cross section due to unparticle contribution dominates over the SM.

As mentioned in paper [4], the unparticle propagator has an extra phase $\exp(-i\pi d_u)$ which can interfere with real photon propagator as well as both real and imaginary part of the Z -boson propagator. The imaginary contribution is quite small compared to real part due to the fact that it is proportional to Z -width. For example, $d_u = 1.5$, only imaginary part will contribute to the cross section which is quite small compared to the real contribution. In Fig.2b, we have shown the angular distribution of the W -pair production. Since W -pair can only be produced through s -channel in unparticle case, the different operator structure will not matter in the experimental determination of cross section (see for example Fig.2b). As mentioned in the above, the new physics contribution starts to show up for $d_u < 1.3$.

3 W -pair production at Hadron collider

The other process of interest to us in W -pair production is proton-proton (anti) collision, $P + P(\bar{P}) \rightarrow W^+ + W^- + X$, where X implies a sum over all unobserved additional debris. In this case both spin-0 and spin-2 unparticle exchange diagram will contribute. At the parton level, the processes are given below (through the effective operators as given in eqns.(1,2)).

$$q(p_1) + \bar{q}(p_2) \rightarrow W^+(p_3) + W^-(p_4) \quad (4)$$

$$g(p_1) + g(p_2) \rightarrow W^+(p_3) + W^-(p_4) \quad (5)$$

The hadronic cross section is defined by convolution of partonic cross section with parton distribution functions and can be written as

$$d\sigma^{H_1 H_2} = \sum_{i,j} \int dx_1 dx_2 f_{i/H_1}(x_1) f_{j/H_2}(x_2) d\hat{\sigma}_{ij}(\hat{s}, \hat{t}_1, \hat{u}_1) + (x_1 \leftrightarrow x_2) \quad (6)$$

where $f_{i/H}(x_i)$ is the probability (usually called parton distribution function, PDF) of emitting a i^{th} -parton with a momentum fraction x_i from a hadron H . The standard partonic mandelstum variables (defined in Appendix) \hat{s} , \hat{t}_1 , \hat{u}_1 are related to the hadronic variables (S , T_1 , U_1) as $\hat{s} = x_1 x_2 S$, $\hat{t}_1 = x_1 T_1$ and $\hat{u}_1 = x_2 U_1$. The $\hat{\sigma}_{ij}$ is the partonic cross section. The above eqn.(6) can be written as

$$S^2 \frac{d^2 \sigma^{H_1 H_2}}{dT_1 dU_1} = \sum_{i,j} \int_{x_{1min}}^1 \frac{dx_1}{x_1} f_{i/H_1}(x_1) \int_{x_{2min}}^1 \frac{dx_2}{x_2} f_{j/H_2}(x_2) \hat{s}^2 \frac{d^2 \hat{\sigma}_{ij}}{d\hat{t}_1 d\hat{u}_1}(\hat{s}, \hat{t}_1, \hat{u}_1) + (x_1 \leftrightarrow x_2) \quad (7)$$

where x_{1min}, x_{2min} are determined by the kinematic conditions

$$\begin{aligned} \hat{s} + \hat{t}_1 + \hat{u}_1 &= 0 & x_1 x_2 S + x_1 T_1 + x_2 U_1 &= 0 & 0 \leq x_1 \leq 1, 0 \leq x_2 \leq 1 \\ x_{1min} &= \frac{-U_1}{S + T_1} & x_{2min} &= \frac{-x_1 T_1}{x_1 S + U_1}. \end{aligned} \quad (8)$$

For our purpose, the double differential partonic cross section $\hat{s}^2 \frac{d^2 \hat{\sigma}_{ij}}{d\hat{t}_1 d\hat{u}_1}(i, j = q, \bar{q} \ \& \ i, j = g, g)$

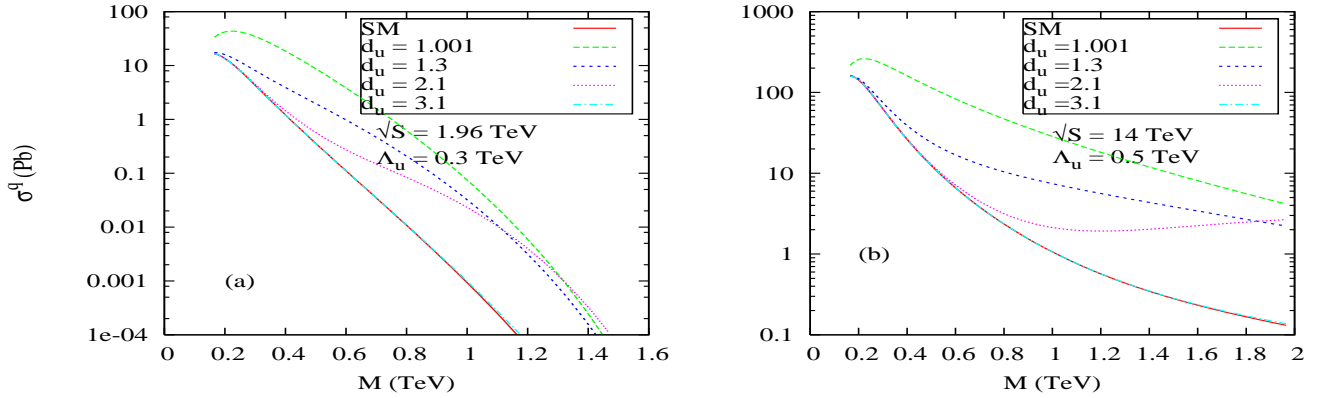


Figure 3: W -pair production cross section versus invariant mass of the W -pair for the $q\bar{q}$ -initiated process at Tevatron (LHC) and $\lambda_2 = 1$. The label “SM” implies only SM cross section.

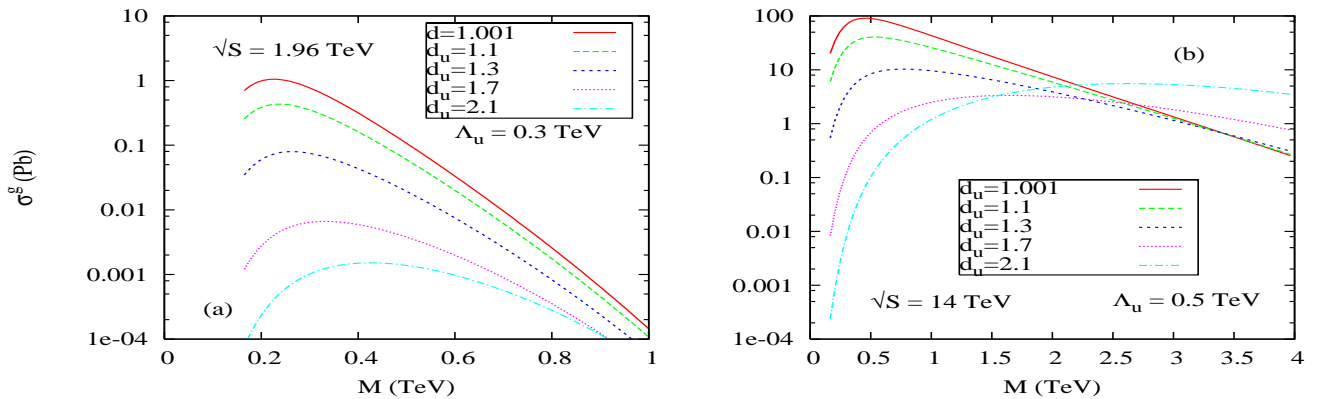


Figure 4: W -pair production cross section versus invariant mass of the W -pair for the gg -initiated process at Tevatron (LHC) and $\lambda_2 = 1$ and $\lambda_0 = 1$.

can be calculated from matrix element square given in Appendix. For numerical computation, we use CTEQ-6L1 parton distributions [48] with scale choice $Q^2 = \hat{s}$ as a factorisation scale.

In Figs.(3, 4) we have plotted the total cross section versus invariant mass of W -pair for both $q\bar{q}$ and gg -initiated processes for various values of d_u . At LHC, gg initiated process dominates over the $q\bar{q}$ process. That is mainly because gluon flux is larger than the $q\bar{q}$ flux. Whereas for Tevatron, it reverses the situation due to low center of mass energy and hence large x_1, x_2 dominated by the $q\bar{q}$ process. In spite of that the cross section of $q\bar{q}$ -initiated process is large due to the presence of scalar interaction in both Tevatron as well as LHC. This is true for rest of the analysis. We have also calculated the $\tau(= \hat{s}/S)$ -distribution for the above mentioned processes as shown in Figs.(5,6). From the figures it is clear that the differential cross section is better than the total cross section for visibility study. This is due to the fact that in the total cross section we are integrating over the phase space as well as the parton momentum fractions x_1 and x_2 .

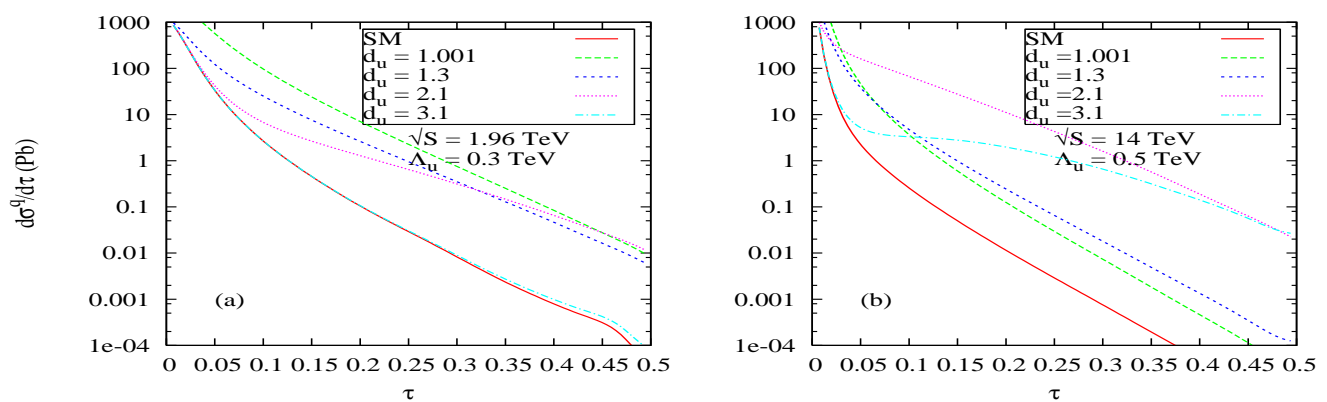


Figure 5: $\tau(= \hat{s}/S)$ -differential distribution for the $q\bar{q}$ -initiated process at Tevatron (LHC) and $\lambda_2 = 1$. The label “SM” implies only SM cross section.

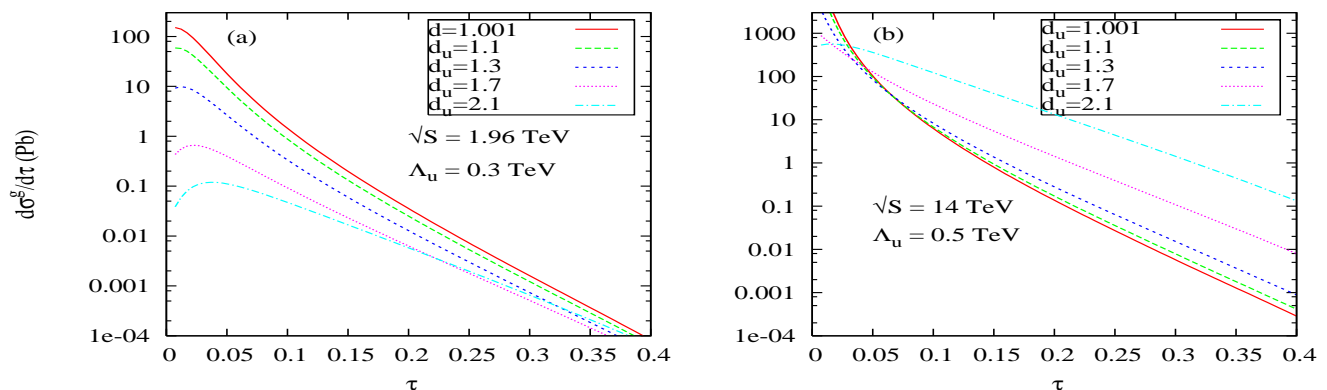


Figure 6: τ -differential distribution for the gg -initiated process at center of mass energy $\sqrt{S} = 1.96(14)$ TeV for Tevatron (LHC) and $\Lambda_u = 0.3(0.5)$ TeV, $\lambda_2 = 1$ and $\lambda_0 = 1$. The label “SM” implies only SM cross section.

In Figs.(7,8), we have plotted the angular distribution for both machines. Here θ is the parton rest frame scattering angle. To get the angular distribution in hadron frame, it has been boosted back to the hadron rest frame. For $q\bar{q}$ -initiated process, the angular distribution is not symmetric at Tevatron due to the fact that the parton distribution functions are not symmetric under interchange of x_1 and x_2 whereas for LHC it is symmetric. At LHC, there is a small dip

at the central region because the spin-2 unparticle exchange dominates over the scalar one for the gg -initiated process.

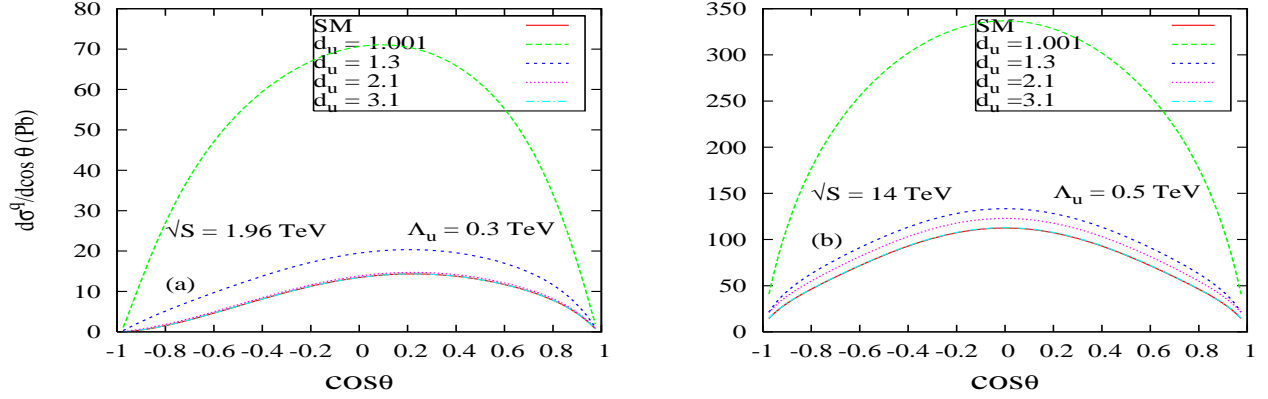


Figure 7: Angular differential distribution of the W -pair production for $q\bar{q}$ -initiated process at Tevatron (LHC) and $\lambda_2 = 1$. The label “SM” implies only SM cross section.

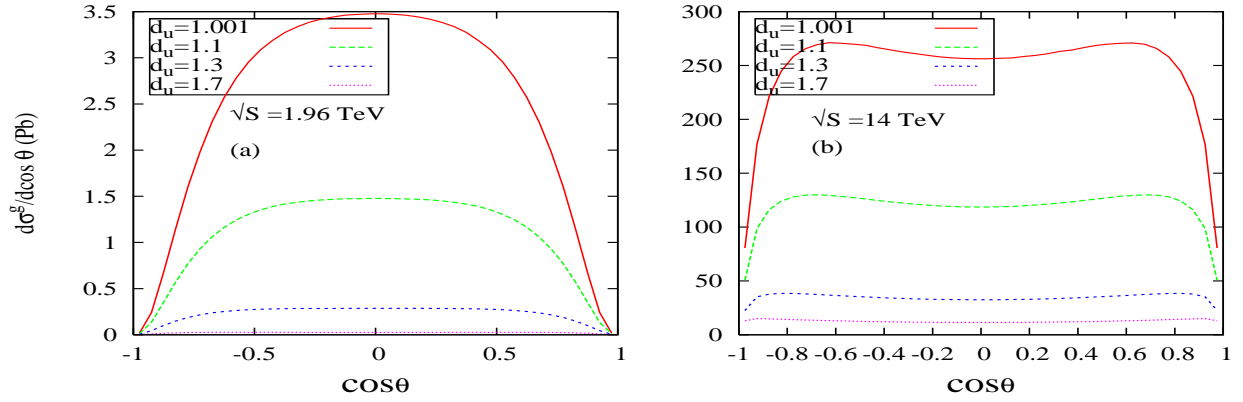


Figure 8: Angular differential distribution of the W -pair production for gg -initiated process at center of mass energy $\sqrt{S} = 1.96(14)$ TeV for Tevatron (LHC) and $\Lambda_U = 0.3(0.5)$ TeV, $\lambda_2 = 1$ and $\lambda_0 = 1$. The label “SM” implies only SM cross section.

In Fig.9 we display the W -pair cross section as a function of Λ_U for various values of d_U for combined ($q\bar{q}$ and gg -initiated) processes. Using the new CDF preliminary result (horizontal lines in Fig.9 at 95% C.L.) on W -pair production [49], we put limits on Λ_U as given in Table.2. For a given value of d_U , the amplitudes scale as $\lambda_0^2/\Lambda_U^{2d_U-1}$ for scalar $q\bar{q}$ -initiated process and $\lambda_i^2/\Lambda_U^{2d_U}$ ($i = 0, 2$) for abovementioned rest of the processes.

d_U	Λ_U (TeV)
1.001	2.14
1.1	1.14
1.3	0.53
1.7	0.29
2.1	0.26

Table.2 Limits on Λ_U from the CDF data [49] at 95% C.L.

The stronger bound comes from the scalar coupling of the unparticle with $q\bar{q}$ due to the fact that the power suppression factor $\Lambda_{\mathcal{U}}$ is less (by one at the amplitude level) than the other couplings. So for fixed $\lambda_i (i = 0, 2) = 1$ the limits increases as $d_{\mathcal{U}}$ decreases from 2.1 to 1.

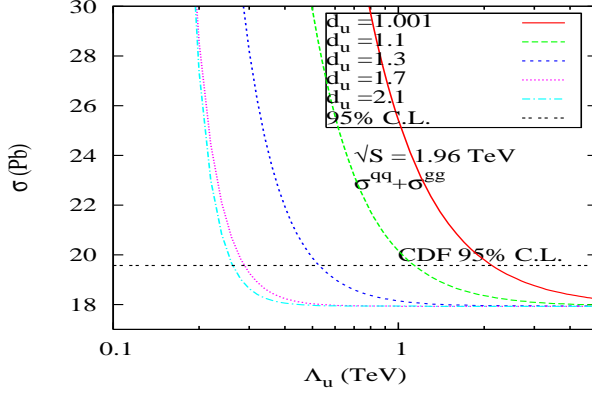


Figure 9: The W -pair production cross section as a function of new scale $\Lambda_{\mathcal{U}}$ with various values of $d_{\mathcal{U}}$ with $\lambda_2 = 1$ and $\lambda_0 = 1$.

4 Conclusion

In this article, we have calculated W -pair production in context of both e^+e^- and hadron collider for various values of non-integral dimension $d_{\mathcal{U}}$. We showed that the scalar coupling of unparticle with fermions is dominated over the other couplings. From the discussion of sections(2,3) we can conclude that for $d_{\mathcal{U}} \leq 1.3$, it is possible to discover the existence of unparticle (if it exists) in current and future colliders. The current measurement of LEP-II data, we put bound on $\Lambda_{\mathcal{U}}$ for different values $d_{\mathcal{U}}$. We also put bound on parameter space $(\Lambda_{\mathcal{U}}, d_{\mathcal{U}})$ with a fixed couplings $\lambda_i = 1 (i = 0, 2)$ at Tevatron. The bounds are strongly dependent on its mass dimension $d_{\mathcal{U}}$. In e^+e^- case, the bound on scale $\Lambda_{\mathcal{U}}$ could be as large as few TeV as $d_{\mathcal{U}}$ close to 1 but for hadronic case, the bound on $\Lambda_{\mathcal{U}}$ is not so large as e^+e^- case because of parton smearing. For larger value of $d_{\mathcal{U}}$, the bounds get weaker by power-law ($\Lambda_{\mathcal{U}}^{2-4d_{\mathcal{U}}}$ and $\Lambda_{\mathcal{U}}^{-4d_{\mathcal{U}}}$). In hadron machine, apart from the $q\bar{q}$ -initiated process, W -pair can be produced from gg -initiated process which is not present in SM (tree level) through the new effective interactions given in eqns.(1,2). This has a large effect compared to SM (specially at LHC). Hence the LHC allows us to investigate the gluonic couplings of the unparticle in the W^+W^- mode and may lead to the discovery of unparticle physics.

Acknowledgements

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5 Appendix

$$s = (p_1 + p_2)^2 ; \quad t = (p_1 - p_3)^2 ; \quad u = (p_1 - p_4)^2 ;$$

$$p_1^2 = 0 ; \quad p_2^2 = 0 ; \quad p_3^2 = m_W^2 ; \quad p_4^2 = m_W^2 ; \quad (9)$$

$$|M_{\mathcal{U}}^S|^2 = |B|^2 s [(s - 2m_W^2)^2 + 2m_W^4] \quad (10)$$

$$|M_{\mathcal{U}}^T|^2 = 8|A'|^2 [4ut(t^2 + u^2) + m_W^2 s(t + u)^2 + 6m_W^2 stu + 6m_W^6 s - 8m_W^8] \quad (11)$$

$$|M_{\gamma+Z}|^2 = 4(|f_L|^2 + |f_R|^2) s^2 \left[\left(\frac{ut}{m_W^4} - 1 \right) \left(\frac{1}{4} - \frac{m_W^2}{s} + \frac{3m_W^4}{s^2} \right) + \frac{s}{m_W^2} - 4 \right] \quad (12)$$

$$|M_t|^2 = g_t^2 \left[\left(\frac{ut}{m_W^4} - 1 \right) \left(\frac{1}{4} + \frac{m_W^4}{t^2} \right) + \frac{s}{m_W^2} \right] \quad (13)$$

$$2Re[M_{\mathcal{U}}^T M_{\gamma+Z}^\dagger] = 8Re[A' (f_L + f_R)] (t - u) [t^2 + u^2 + 4m_W^2 s - 2m_W^4] \quad (14)$$

$$2Re[M_{\mathcal{U}}^T M_t^\dagger] = 4Re[A' g_t] \left[2t^2 + 2t(s - 3m_W^2) + (s^2 - 2m_W^2 s + 6m_W^4 - \frac{2m_W^6}{t}) \right] \quad (15)$$

$$2Re[M_{\gamma+Z} M_t^\dagger] = 4Re[f_L g_t] s \left[\left(\frac{ut}{m_W^4} - 1 \right) \left(\frac{1}{4} - \frac{m_W^2}{2s} - \frac{m_W^4}{st} \right) + \frac{s}{m_W^2} - 2 + \frac{2m_W^2}{t} \right] \quad (16)$$

$$|M_{gg}|^2 = 32|A'|^2 (t^4 + u^4 - 4m_W^2(t^3 + u^3) + 4m_W^4(2t^2 + 2u^2 + tu) - 12m_W^6(t + u) + 10m_W^8)$$

$$+ 64|B'|^2 ((t + u)^4 - 4m_W^2(t + u)^3 + 6m_W^4(t + u)^2 - 8m_W^6(t + u) + 8m_W^8) \quad (17)$$

$$g_t = g \quad (\text{for lepton})$$

$$= gV_{pn} \quad (V_{pn} \text{ is the CKM mixing matrix } p = (u, c, t) \text{ } n = (d, s, b)) \quad (18)$$

$$f_L = \frac{e^2 e_f}{s} + \frac{g^2 g_L}{2(s - m_Z^2 + im_Z \Gamma_Z)} ; \quad g \sin \theta_W = e$$

$$f_R = \frac{e^2 e_f}{s} + \frac{g^2 g_R}{2(s - m_Z^2 + im_Z \Gamma_Z)} ; \quad m_W^2 = \cos^2 \theta_W m_Z^2$$

$$g_L = C_v^f + C_A^f ; \quad g_R = C_v^f - C_A^f ; \quad C_v^f = T_3^f - 2Q_f \sin^2 \theta_W ; \quad C_A^f = T_3^f \quad (19)$$

$$A' = \frac{\lambda_2^2 Z_{d\mathcal{U}}}{4\Lambda_{\mathcal{U}}^4} \left(\frac{-s}{\Lambda_{\mathcal{U}}^2} \right)^{d_{\mathcal{U}}-2} \quad B = \frac{4\lambda_0^2 Z_{d\mathcal{U}}}{\Lambda_{\mathcal{U}}^3} \left(\frac{-s}{\Lambda_{\mathcal{U}}^2} \right)^{d_{\mathcal{U}}-2} \quad B' = \frac{\lambda_0^2 Z_{d\mathcal{U}}}{\Lambda_{\mathcal{U}}^4} \left(\frac{-s}{\Lambda_{\mathcal{U}}^2} \right)^{d_{\mathcal{U}}-2} \quad (20)$$

References

- [1] S. Coleman and E. Weinberg, Phys.Rev.**D7** (1973) 1888.
- [2] H. Georgi, Phys. Rev. Lett. **98** (2007) 221601 [arXiv:hep-ph/0703260].
- [3] T. Banks and A. Zaks, Nucl. Phys. **B196** (1982) 189.
- [4] H. Georgi, [arXiv:hep-ph/07042457].
- [5] K. Cheung, W. Y. Keung and T. C. Yuan, arXiv:0706.3155 [hep-ph].
- [6] K. Cheung, W. Y. Keung and T. C. Yuan, Phys. Rev. Lett. **99**, 051803 (2007) [arXiv:0704.2588 [hep-ph]]; arXiv:0706.3155 [hep-ph].
- [7] M. X. Luo and G. H. Zhu, arXiv:0704.3532 [hep-ph]; M. X. Luo, W. Wu and G. H. Zhu, arXiv:0708.0671 [hep-ph].
- [8] C. H. Chen and C. Q. Geng, arXiv:0705.0689 [hep-ph]; Phys. Rev. **D76**, 036007 (2007) [arXiv:0706.0850 [hep-ph]]; arXiv:0709.0235 [hep-ph].
- [9] G. J. Ding and M. L. Yan, arXiv:0705.0794 [hep-ph]; arXiv:0706.0325 [hep-ph].
- [10] Y. Liao, arXiv:0705.0837 [hep-ph]; arXiv:0708.3327 [hep-ph]; Y. Liao and J. Y. Liu, arXiv:0706.1284 [hep-ph].
- [11] T. M. Aliev, A. S. Cornell and N. Gaur, arXiv:0705.1326 [hep-ph]; JHEP **07**, 072 (2007) [arXiv:0705.4542 [hep-ph]].
- [12] S. Catterall and F. Sannino, Phys. Rev. **D76**, 034504 (2007) [arXiv:0705.1664 [hep-lat]].
- [13] X. Q. Li and Z. T. Wei, Phys. Lett. **B651**, 380 (2007) [arXiv:0705.1821 [hep-ph]]; arXiv:0707.2285 [hep-ph].
- [14] C. D. Lu, W. Wang and Y. M. Wang, arXiv:0705.2909 [hep-ph].
- [15] M. A. Stephanov, arXiv:0705.3049 [hep-ph].
- [16] P. J. Fox, A. Rajaraman and Y. Shirman, arXiv:0705.3092 [hep-ph].
- [17] N. Greiner, arXiv:0705.3518 [hep-ph].
- [18] H. Davoudiasl, arXiv:0705.3636 [hep-ph].
- [19] D. Choudhury, D. K. Ghosh and Mamta, arXiv:0705.3637 [hep-ph].
- [20] S. L. Chen and X. G. He, arXiv:0705.3946 [hep-ph]; S. L. Chen, X. G. He and H. C. Tsai, arXiv:0707.0187 [hep-ph].
- [21] P. Mathews and V. Ravindran, arXiv:0705.4599 [hep-ph].
- [22] S. Zhou, arXiv:0706.0302 [hep-ph].
- [23] R. Foadi, M. T. Frandsen, T. A. Ryttov and F. Sannino, arXiv:0706.1696 [hep-ph].

- [24] M. Bander, J. L. Feng, A. Rajaraman and Y. Shirman, arXiv:0706.2677 [hep-ph].
- [25] T. G. Rizzo, arXiv:0706.3025 [hep-ph].
- [26] H. Goldberg and P. Nath, arXiv:0706.3898 [hep-ph].
- [27] R. Zwicky, arXiv:0707.0677 [hep-ph].
- [28] T. Kikuchi and N. Okada, arXiv:0707.0893 [hep-ph].
- [29] R. Mohanta and A. K. Giri, arXiv:0707.1234 [hep-ph]; arXiv:0707.3308 [hep-ph].
- [30] C. S. Huang and X. H. Wu, arXiv:0707.1268 [hep-ph].
- [31] N. V. Krasnikov, arXiv:0707.1419 [hep-ph].
- [32] A. Lenz, arXiv:0707.1535 [hep-ph].
- [33] D. Choudhury and D. K. Ghosh, arXiv:0707.2074 [hep-ph].
- [34] H. Zhang, C. S. Li and Z. Li, arXiv:0707.2132 [hep-ph].
- [35] Y. Nakayama, arXiv:0707.2451 [hep-ph].
- [36] N. G. Deshpande, X. G. He and J. Jiang, arXiv:0707.2959 [hep-ph]; N. G. Deshpande, S. D. H. Hsu and J. Jiang, arXiv:0708.2735 [hep-ph].
- [37] A. Delgado, J. R. Espinosa and M. Quiros, arXiv:0707.4309 [hep-ph].
- [38] M. Neubert, arXiv:0708.0036 [hep-ph].
- [39] S. Hannestad, G. Raffelt and Y. Y. Y. Wong, arXiv:0708.1404 [hep-ph].
- [40] P. K. Das, arXiv:0708.2812 [hep-ph].
- [41] G. Bhattacharyya, D. Choudhury and D. K. Ghosh, arXiv:0708.2835 [hep-ph].
- [42] D. Majumdar, arXiv:0708.3485 [hep-ph].
- [43] A. T. Alan and N. K. Pak, arXiv:0708.3802 [hep-ph].
- [44] A. Freitas and D. Wyler, arXiv:0708.4339 [hep-ph].
- [45] L. Anchordoqui and H. Goldberg, arXiv:0709.0678 [hep-ph].
- [46] T. A. Ryttov and F. Sannino, arXiv:0707.3166 [hep-th].
- [47] OPAL Collaborations, Phys. Lett. **B493** (2000) 249;
OPAL Collaborations and OPAL Physics Note PN437.
- [48] J. Pumplin *et. al.* JHEP **0207** (2002) 012.
- [49] M.S. Neubauer [CDF and D0 Collab.] arXiv:hep-ex/0605066.